LESSON 4

Rationale for SO_2 Monitor Siting Criteria

Goal

To familiarize you with the logic of the SO_2 monitor siting criteria.

Objectives

At the end of this lesson, you will be able to:

1 associate assumed undue influence SO_2 concentration levels with the effects of SO_2 sources in rural, urban, and suburban areas.

2 describe assumptions for determining interference distances.

3 differentiate between the relative influences of a nearby SO_2 source on SO_2 monitoring stations within and outside the source's 10 degree plume sector.

4 recognize topographic effects on the shape of an air parcel and on wind speed.

5 define mechanical turbulence.

6 recognize the averaging effect of an air cavity on pollutant concentration.

7 describe the causes of upslope and downslope air flows.

8 recognize the effects of obstacles on air flows under stable and unstable atmospheric conditions.

9 recognize the effect of ambient temperature on SO_2 emission rates.

10 associate assumed SO_2 half-lives with areas having populations greater than and less than one million.

Procedure

1. Read pages 83-102 of EPA-450/3-77-013 *Optimum Site Exposure Criteria for SO_2 Monitoring.*
2. Complete the review exercise for this lesson.
3. Check your answers against the answer key following the exercise.
4. Review the pages in the reading for any questions you missed.
5. Take Quiz 2 in the back of this book. Review the pages in the reading for any questions you missed.
6. Continue to Lesson 5.

Estimated student completion time: 6 hours

Reading Assignment Topics

- Undue influence effects of nearby SO_2 sources
- Meteorological processes pertinent to monitor siting
- Effect of ambient temperature on SO_2 emission rates
- Chemical and physical interactions of SO_2 pertinent to monitor siting

Reading Guidance

Refer often to the figures of the assigned reading material as you progress through the assignment.

Try to visualize how the siting criteria would be affected if the assumptions described in this reading assignment were altered.

Review Exercise

Now that you've completed the assignment for Lesson 4, please answer the following questions to determine whether or not you are mastering the material.

Select the values that were assumed for each of the following parameters in determining the regional scale interference distance for a major urban area. (Questions 1-5)

1. Wind speed (m/s):
   a. 0.1
   b. 1
   c. 10
   d. 15
2. Half-life of SO_2 (hours):
   a. 6
   b. 12
   c. 24
   d. 3
3. Averaging interval of monitoring site SO_2 concentrations (hours):
   a. 1
   b. 3
   c. 24
   d. none of the above
4. SO_2 emission rate for a major urban area ($g/s/m^2$):
   a. 0.75×10^{-6}
   b. 0.63×10^{-4}
   c. 0.86×10^{-5}
   d. 0.72×10^{-3}
5. Undue influence SO_2 concentration level (mg/m^3):
   a. 0.1
   b. 2.6
   c. 25
   d. 50

Select the values that were assumed for each of the following parameters in determining the point source, minor source, and source interference distances (PSID, MSID, and SID, respectively). (Questions 6-10)

6. Effective SO_2 emission height (m):

   a. zero

   b. 10

   c. 15

   d. 25

7. Undue influence SO_2 concentration level (mg/m^3):

   a. 1

   b. 10

   c. 100

   d. 500

8. Wind speed (m/s):

   a. 0.1

   b. 1

   c. 10

   d. 15

9. Atmospheric stability class:

   a. A

   b. B

   c. C

   d. D

10. Averaging interval of monitoring site SO_2 concentrations (hours):

    a. 0.5

    b. 1

    c. 3

    d. 24

11. An SO_2 source has __________ influence on SO_2 concentrations measured at monitoring sites *within* its 10 degree plume sector than at sites *outside* its 10 degree plume sector.

    a. more

    b. less

    c. the same

12. As an air parcel passes between two obstructions, the parcel is squeezed ________ and its speed ________.

    a. vertically, increases

    b. vertically, decreases

    c. horizontally, increases

    d. horizontally, decreases

13. As an air parcel passes over a mountain, the parcel is squeezed ________ and its speed ________.

    a. vertically, increases

    b. vertically, decreases

    c. horizontally, increases

    d. horizontally, decreases

14. As an air parcel passes across a valley, the parcel expands ________ and its speed ________.

    a. vertically, increases

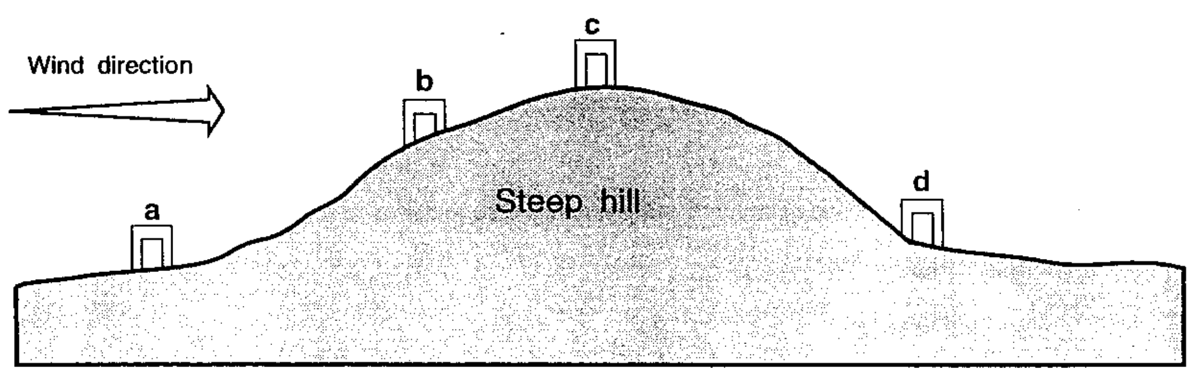
    b. vertically, decreases

    c. horizontally, increases

    d. horizontally, decreases

15. True or False? Mechanical turbulence is produced when air moves over a rough surface.

16. Which of the locations, labeled a through d, would be the most likely site of an air cavity wake?



17. An air cavity tends to ________ pollutant concentrations.

    a. average

    b. increase

    c. decrease

18. True or False? When the general wind direction is oblique to a ridge-valley axis, channeling of the wind often occurs.

19. Mountain passes ________ wind speeds.

    a. increase

    b. decrease

    c. have no effect on

20. At night, ________ air flows are caused by ________ of the air adjacent to the ground along a valley floor and slope.

    a. downslope, heating

    b. downslope, cooling

    c. upslope, heating

    d. upslope, cooling

21. In the daytime, ________ air flows are caused by ________ of the air adjacent to the ground along a valley floor and slope.

    a. downslope, heating

    b. downslope, cooling

    c. upslope, heating

    d. upslope, cooling

22. Under ________ atmospheric conditions, air parcels tend to move ________ obstacles.

    a. unstable, around

    b. stable, over

    c. unstable, over

    d. none of the above

23. Under ________ atmospheric conditions, air parcels tend to move ________ obstacles.

    a. stable, around

    b. unstable, around

    c. stable, over

    d. none of the above

24. True or False? The urban heat-island effect causes air to flow into urban centers at night.

25. True or False? The pollutant averaging effects of building wakes and air cavity flows cause the SO_2 concentration distribution of a city to be uniform up to at least the mean building height.

26. True or False? Ambient temperature may influence the rate of SO_2 emissions.

27. The SO_2 monitoring criteria are based on an assumed SO_2 half-life of ________ hour(s) for cities with populations greater than one million, and ________ hour(s) for cities with populations of one million or less.

    a. 1, 10

    b. 10, 1

    c. 1, 3

    d. 3, 10

Review Exercise Answers

		Page*
1.	b	84
2.	d	84
3.	b	84
4.	c	84
5.	b	84
6.	a	85
7.	b	85
8.	b	85
9.	d	85
10.	c	85
11.	a	87
12.	c	88
13.	a	88
14.	b	88
15.	True	89
16.	d	89
17.	a	89
18.	True	90
19.	a	90
20.	b	90
21.	c	90

* Refer to pages 83-102 of EPA-450/3-77-013 *Optimum Site Exposure Criteria for SO_2 Monitoring.*

22. c 91

23. a 91

24. True 92

25. True 95-96

26. True 99

27. c 102

Now take Quiz 2 in the back of this book. Review the pages in the reading for any questions you missed.

Then continue to Lesson 5.

5.0 RATIONALE AND SUPPORT DOCUMENTATION FOR SITING CRITERIA

The site selection and inlet placement procedures and criteria discussed in Section 4.0 are quite specific, particularly those regarding location parameters such as height of the inlet, proximities of interfering sources (undue influence) and horizontal positioning of the inlet for rooftop sties, etc. The rationale for some of these procedures and siting approaches was included to explain certain points of the procedural logic. However, it was felt that justifying certain other elements of the siting procedures and criteria would have muddled the continuity. Therefore, we have reserved this section for their presentation.

The logic underlying the procedures of Section 4.0 can be considered embodied in three basic elements:

1) Determining the general location of the monitoring site, mainly via simulation modeling.

2) Refining the location to minimize undue influences from nearby sources, including meteorological effects.

3) Placing the instrument inlet in such a location to avoid local contamination.

The first element, we believe, has been adequately covered in previous sections and in the appendices and requires no further discussion here. Therefore, much of the material presented in this section will pertain to elements 2 and 3. Several miscellaneous items that are relevant to all three elements will also be discussed.

5.1 UNDUE INFLUENCE EFFECTS

Regarding the problem of establishing a site location such that undue influences from nearby sources are minimized,* we had to first define what constituted undue influence. We wanted to use a fairly stable, maximum SO_2 concentration as a level of undue influence and then establish a separation distance between the monitoring site and all sources such that any one source's contribution at the monitoring site would not exceed the undue

* In just about every reference cited in this study the problem of undue influence of nearby sources was mentioned, but no objective procedures or approaches for dealing with such influences were ever suggested.

influence level. Typical rural background levels over all parts of the country seemed to be excessive, 10-30 $\mu g/m^3$ (viz., Figure 4-3, EPA,1974d), to be used as an undue influence level for regional-scale stations. Also, these levels were decreasing due to the effectiveness of SO_2 emission controls. Thus, it was decided to use the natural background level of 2.6 $\mu g/m^3$ (1 ppb) as reported by Robinson and Robbins (1970), a very low level and probably quite stable as well. Using this value and typical emission rates for various classes and configurations of sources, we determined sets of distances beyond which impacts from any source did not exceed the undue influence level. Examples of these distances, described as "interference distances" (IDs), were shown in Table 4-2 (see Page 34).

The ID of a major urban area was determined by using the normalized concentration pattern resulting from a circular area source as shown in Figure 5-1 (from Ludwig and Kealoha, 1975) along with a speed of 1 m/sec and a half-life value of 3 hours.* Typical maximum emission rates for a major urban area were assumed to be represented by the city of Philadelphia, $Q = 0.86 \times 10^{-5}$ g/sec/m^2 (from EPA,1973b). This gave an ID of about 30 km.

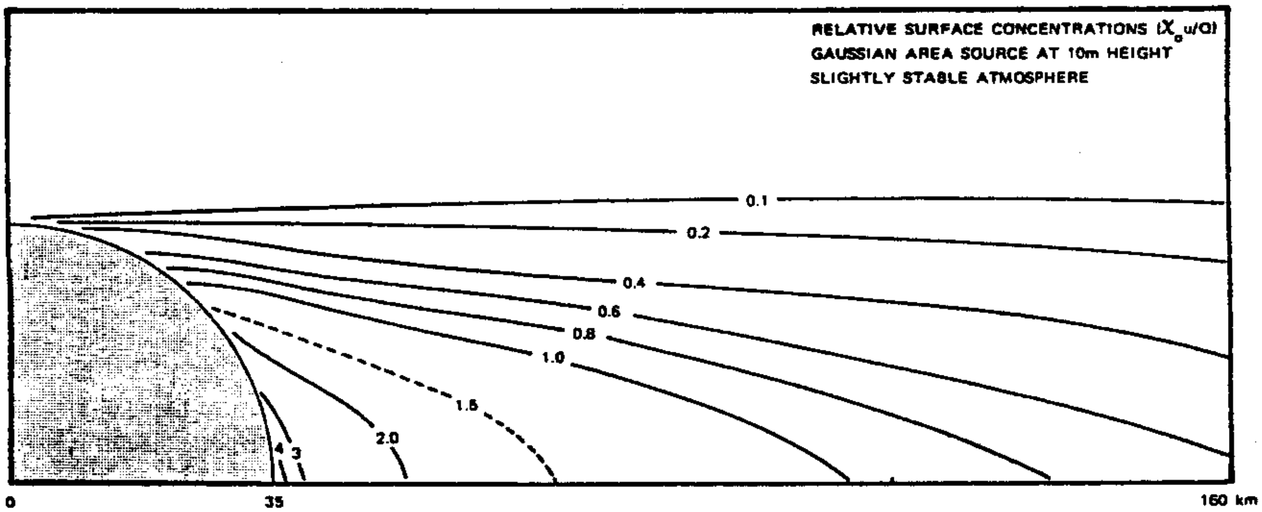


FIGURE 5-1. Normalized concentrations computed with a Gaussian dispersion model (taken from Ludwig and Kealoha, 1975).

The IDs of the other source types associated with regional-scale stations (see Table 4-2, Page 34) were determined via solutions to the Gaussian equation; typical source configurations and emission rates assumed are shown in Table 5-1. The ID calculations were based on a 3-hour average concentration at the monitoring site. A 3-hour half-life for SO_2 was assumed for all source types, except the individual home where a value of infinity was assumed. A reduction factor of 0.51 was utilized to convert the quasi-instantaneous concentration estimates to 3-hour averaging times as suggested by Turner (1974). The IDs of the various sized towns shown in Table 4-2 (Page 34) were determined by assuming that the concentration varied as the inverse of the square of the distance from the source (town) to the monitoring site.

* See Section 5.3 for discussion of SO_2 decay characteristics.

TABLE 5-1

Configurations and Emissions for Typical Source Types Assumed in Determining Interference Distances for Regional-Scale Stations

Source Type	Characteristic Emission Period	Fuel Rate S Content (%)	Source Configuration	Emission Rate (g/sec)	Meteorology		Effective Ht. (m)
					Wind Speed	Stability Class	
Power Plant (400 MW)	365 days/yr	280×10^6 gal #6 oil @ 1% S	Point, Uniform Wind over 22.5° Sector	575	5 m/sec	D	300
Industrial Space Heat (500 T SO_2/yr)	Winter Quarter (Dec, Jan, Feb)	14×10^6 gal #6 oil @ 0.5% S	Point	58	5 m/sec	D	200
Small Town (25,000 pop., 6000 homes)	Winter Quarter (Dec, Jan, Feb)	10^3 gal/home #2 oil @ 0.2% S	Area Source 4 mi^2	10	1 m/sec	D	0
Individual Home	Winter Quarter (Dec, Jan, Feb)	10^3 gal #2 oil @ 0.2% S	Point	.0016	1 m/sec	F	0

During this phase of the study, we concluded that a major urban area, in an ID sense, may be considered as having a population of about 2×10^5 or more. This contention was based on the observation that the ID varied more closely with emission intensity rather than with total emissions; large cities emit more SO_2 than small cities, but it is emitted over a larger area. For example, the ID for a 25×10^3 population town was 15 km (Table 4-2) versus an ID of 30 km for a 1×10^6 population city; the 2×10^5 figure seemed an appropriate cut-off point to separate the large urban areas from smaller towns.

Analogous to the IDs for regional-scale stations is the concept of point, minor, and source IDs (PSID, MSID, and SID, respectively), as presented in Table 4-4 (see Page 44). These values were obtained by considering an undue influence level of 10 μg/m^3 (instead of 2.6 μg/m^3), which was the cleanest rural SO_2 background level observed. We felt that using this higher undue influence level was justified since the associated ID values are meant to apply in urban and suburban areas where existing SO_2 levels are much higher than in rural areas where regional-scale station IDs apply. Table 5-2 shows how the IDs of Table 4-4 were obtained. In developing the concentrations shown, zero effective height, a wind speed of 1 m/sec and stability class D were assumed; this would tend to produce a maximum impact at the site to provide a modest safety factor. The diffusion coefficients used in the calculations were those suggested by Bowne (1973) for rural, suburban, and urban areas. Large point sources were considered as those using 10^6 gal/yr of fuel oil. Minor sources used 10^3 gallons in rural areas (home), 10^4 gallons in suburban areas (small office building) and 10^5 gallons in urban areas (large office building). All fuel was burned during the winter quarter of the year. The concentrations as shown in Table 5-2 are unadjusted--that is, the concentrations have not been modified to account for effects due to decay and averaging time; the actual 3-hr mean concentrations were estimated by multiplying the given concentrations by an appropriate half-life factor (considering corresponding travel time) and the correction factor of 0.51 to account for additional dilution due to wind direction variability. Multiplying the circled numbers in Table 5-2 by these factors will result in an actual concentration estimate of 10 μg/m^3

Downwind distances associated with these concentrations that are shown in Table 5-2 are the IDs of Table 4-4.

TABLE 5-2

Rationale for PSIDs and MSIDs of Table 4-4 (see Page 44)

Development Intensity	Unadjusted Concentration (μg/m³)											
	Urban				Suburban				Rural			
Fuel Use (gal/yr) / Downward Distance (m)	10^3*	10^4	10^5	10^6†	10^3	10^4	10^5	10^6	10^3	10^4	10^5	10^6
10	5.1	51	510	---	15.9	159	---	---	84.9	849	---	---
30	3.4	34	340	---	9.8	98	980	---	52.5	525	---	---
100	0.9	9	90	900	3.07	30.7	307	---	11.3	113	---	---
300	0.23	2.3	23	230	.68	6.8	68	680	1.6	16	160	---
600	.078	.78	7.8	78	.26	2.6	26	260	.5	5.0	50	500
1000	.034	.34	3.4	34	.117	1.17	11.7	117	.20	2.0	20	200
2000	.011	.11	1.1	11	.04	.4	4.0	40	.073	.73	7.3	73
3000	.006	.06	.58	5.8	.021	.213	2.13	21.3	.038	.38	3.8	38

* Individual Home
† Large Point Source

A 10° plume sector roughly corresponds to ± 1σ around the centerline of the plume. This sector width is suggested as a guide for determining those upwind sources that may unduly influence the measurements at the site. The schematic shown in Figure 5-2 illustrates the rationale for this criterion. For neighborhood-scale stations, the sector sizes were increased to 20° for the very nearby point sources.

5.2 METEOROLOGICAL PROCESSES PERTINENT TO SITE LOCATION REFINEMENT AND INLET PLACEMENT

Wind direction establishes the general transport direction and determines which sector of the area surrounding the source will receive the pollutant.

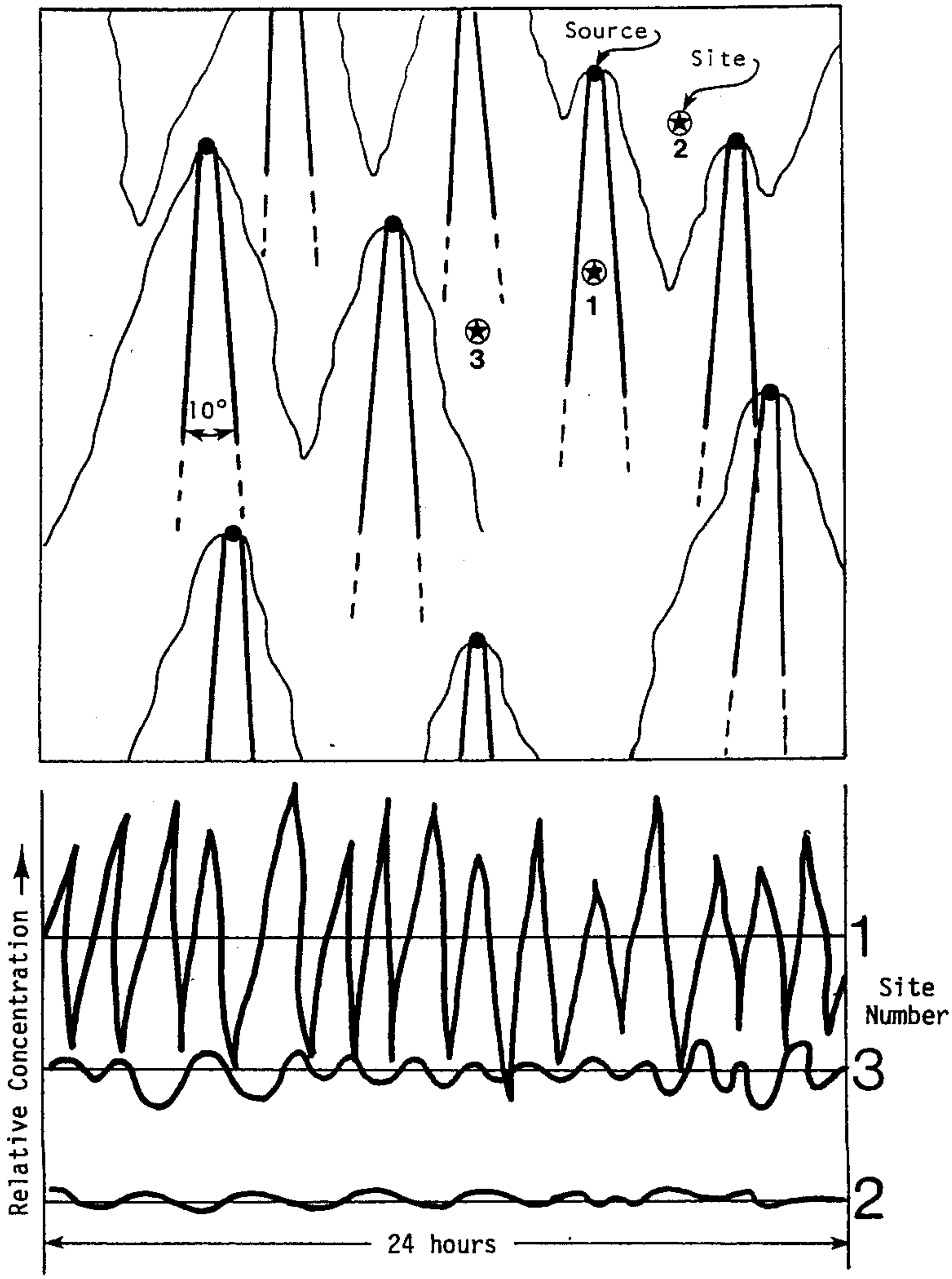


FIGURE 5-2. Schematic illustrating undue influence of nearby sources on measurements at three sampling sites: (1) within 10° plume sector; (2) at a minimum impact point within area; and (3) at a point beyond the MSID but within zone of concentration characteristic of the area as a whole.

The location of impact points within the sector are determined by the trajectory of the polluted air stream or parcel. The trajectory is only rarely a straight line--the parcel being subject to effects of obstructions that can change a given direction to another. These obstructions include mountains, valleys, buildings, and other parcels or masses of air. Even in the absence of physical obstructions, the wind varies in space and time due to thermal effects, shear effects, and turbulence advected from upwind (e.g., Fig. 6, Anderson, 1971).

The parcel may also be deformed; being a fluid, the air parcel will be subject to changes in shape and separation. However, from mass continuity considerations, there must also be corresponding changes in air flow. For example, parcels passing between two obstructions (viz., two buildings) or over a mountain will be squeezed horizontally (transverse) and vertically, respectively. In either situation, stretching of the parcel longitudinally will take place to compensate, resulting in a faster air flow. The reverse will occur for parcels moving across a valley (vertical stretching and longitudinal squeezing) (see Fig. 5-3). However, from mass continuity considerations, the concentration of the pollutant within the parcel must remain essentially the same throughout the deformation process.

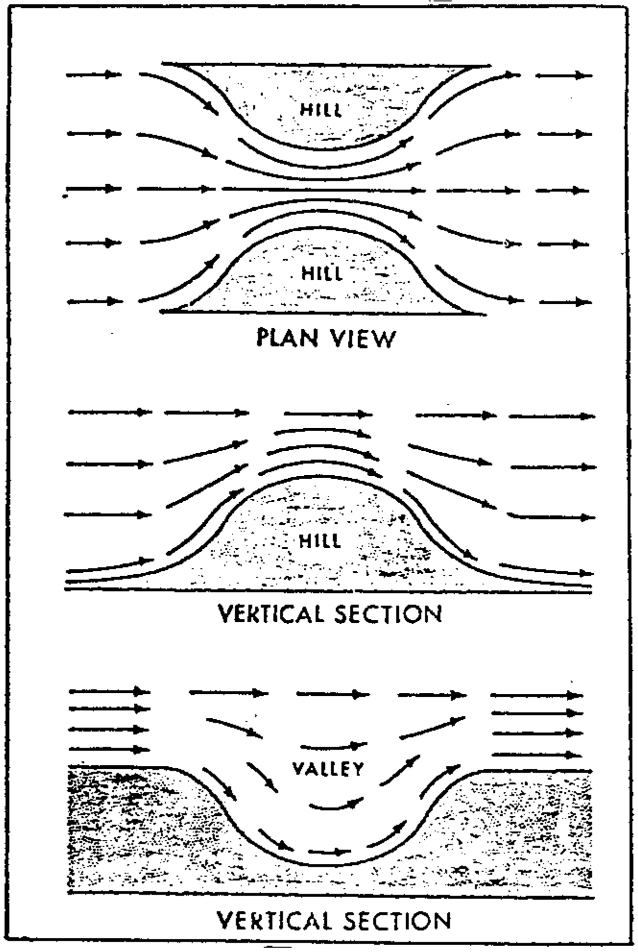


FIGURE 5-3. Topography effects on wind. Length of arrow is proportional to the wind speed.

In illustrating the concepts of wind speed and direction, and deformation, we have assumed that the pollutant remains contained within the parcel as the parcel proceeds downwind. This is not actually the case because turbulent mixing and diffusion processes are constantly at work dispersing the pollutant from the initial parcel to adjacent ones as the pollutant plume moves downwind. [Note in this regard, a point apparently missed in some of the papers reviewed that no physical mechanism exists in the atmosphere, including deformation, which can reverse the process and "unmix" the atmosphere to create higher concentrations of SO_2. Therefore, turbulence in the atmosphere can only lead to dilution or dispersion of a polluted air mass that it affects; "cavity" flows cannot accumulate pollutant--they can only partically contain it; nor can "channeling", i.e., the squeezing of streamlines, squeeze together the pollutant and increase its concentration. Indeed, no flow nor even a stagnant air mass can contain a higher pollutant concentration than that of its most intense inlet.] The rate of diffusion is a function of atmospheric stability, which is associated with varying degress of thermal or convective turbulence and the degree and nature of the roughness of the surface over which the parcels are transported, which is associated with varying degrees of mechanical turbulence.

Mechanical turbulence is produced when air moves over a rough surface, which tends to interrupt an otherwise smooth air flow. Air swirling about buildings, rough ground, and clumps of irregular sized vegetation are examples of mechanical turbulence. The degree of mechanical turbulence is directly proportional to the wind speed.

5.2.1 Effects of Natural Topography: Wakes, Channeling, and Turbulence

The transport and diffusion of a pollutant plume is complicated by the effects of natural terrain features on the flow of air in which the plume is transported.

It is suggested on the basis of work described by Anderson (1973), that topographic effects on the windfield are scaled by the ratio of topographic slopes to the depth of the mixing layer. That is, if the ground rises or falls a significant fraction of the mixing layer depth, the wind speed components should change a comparable fraction; for mixing depths on the order of 1000 ft, 100-ft elevations would usually be significant. Topographic features considerably larger than this can produce even more dramatic changes in the flow field. For example, wind flowing towards a very steep hill face is merely guided by the topography, but wind blowing off the top of a similar face will typically break up into severe turbulence and may even form a "cavity wake" as shown in Figure 5-4. (For a good review of the basic mechanism that causes wakes and wake cavities, the reader is referred to Halitsky, 1962.).

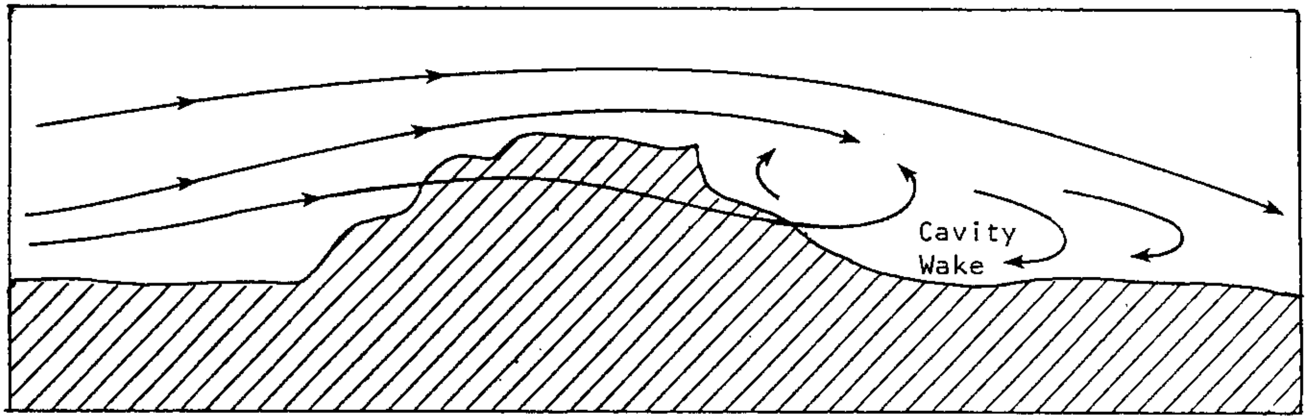


FIGURE 5-4. Assymmetry of flow approaching and leaving steep topography.

If topographic slopes exceed 10 percent, much increased turbulence can be expected with downslope winds. If topographic slopes exceed 20 percent, cavity flows are quite possible.

Inasmuch as the air entering a cavity may turn over many times before leaving, the cavity tends to average the concentration from the pollution sources that feed it. If the pollutant enters from the flow passing the obstacle, it may be thought of as continuously "sampling" the passing air, mixing it up, and passing it on much delayed. Thus, the cavity averages on both time (due to the delay) and space (due to its size) scales. The cavity cannot "collect" pollutant because it also "collects" the air which carries the pollutant, each in direct ratio to its concentration.

When the general wind direction is oblique to a ridge-valley axis, the channeling of the wind often occurs as shown in Figure 5-5. The surface wind speed in the valley is usually diminished because of friction (Flemming, 1967) If the valley wall is bluff, wake cavities (mechanical turbulence) on the lee side of the upwind wall may be produced. Wind blowing perpendicular to the valley axis will not be significantly channeled, but surface speeds can be considerably diminished (frictional drag and vertical stretching) and the probability and size of wake cavities will increase.

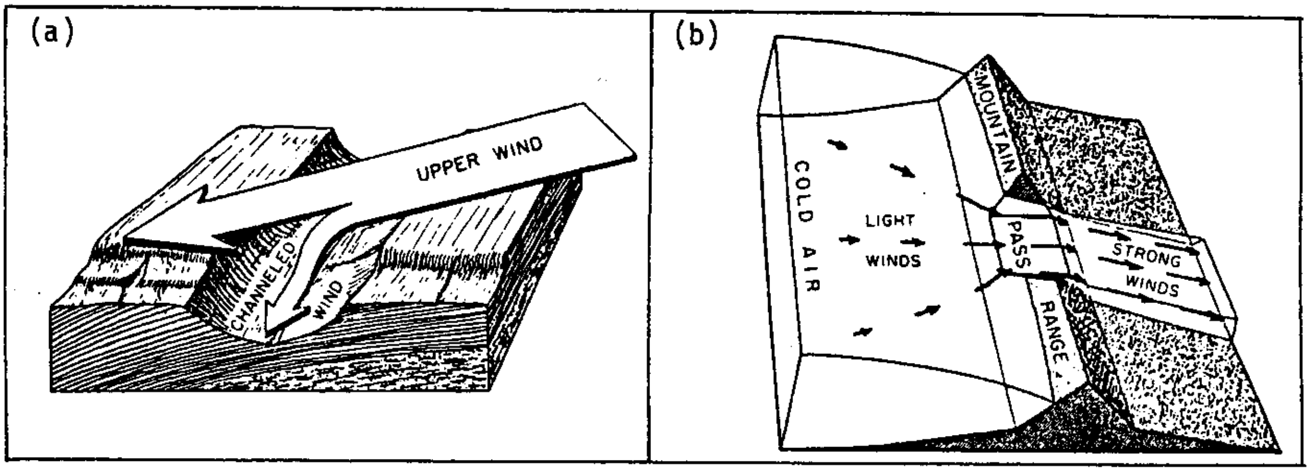


FIGURE 5-5. Distortions of the wind flow by topographic obstacles.
(a) Channeling of the wind by a valley, and
(b) The effect of a mountain pass on the wind flow.
(Taken from Slade, 1968.)

At night under clear skies and light winds, the air adjacent to the ground along the valley floor and slope are cooled through radiational cooling. As this cooling progresses, a density differential between air at the same elevation (relative to a horizontal plane) develops and results in a flow of air down the slope toward the valley floor. This flow is called a slope or drainage wind. The same mechanism also causes a flow of air downhill along the valley axis (valley wind). In the daytime under light wind conditions, the drainage flow mechanism is reversed and causes upslope and upvalley flows. Downslope and upslope air flows can be complicated in complex valley systems where several valleys merge at various angles or where slopes vary. Also, the differential heating of valley slopes can further complicate the already complex flow pattern.

The only significant modification of winds and turbulence (and hence SO_2 concentrations) due to irregular topography is that it increases mechanical turbulence. The scales of this turbulence depend on the strength of the wind and the size and size distribution of the individual features. If the features are large, wake cavities may form; otherwise the turbulence elements are of small scale. If the area is generally level, flows produced by drainage and valley flow mechanisms will be insignificant. In general, smooth hills alter the flow least. Under unstable conditions, air parcels tend to move over obstacles, while under stable conditions, air parcels tend to move around obstacles. In strong winds, cavity wakes can form on the lee side of large bluff hills.

Trees can obstruct an otherwise smooth wind flow and increase mechanical turbulence. Dense clumps of large trees can have the same effect on wind flow as a small, bluff hill and produce wake cavities. Similarly, wake cavities may exist on the windward side of a forest clearing. Below a forest canopy, wind speeds may be very low and diurnal temperature variations tempered. Irregularly spaced trees or small clumps of trees of varying height, lines of trees, and low vegetation will have the same effect as rough topography and increase mechanical turbulence.

5.2.1.1 Effects of Above Considerations on SO_2 Distribution

The effects of ridge-valley topography on SO_2 concentrations and patterns depend on several factors. The major factors are the time of day the pollutants are being emitted, where they are being emitted, the height of release, and the prevailing meteorology. An SO_2 plume emitted from the top of the valley wall or on an adjoining plateau may be caught up in a cavity wake (downwash) and brought down into the valley. At night, an SO_2 plume released at a high level at a high exit velocity may escape the valley and surrounding high terrain entirely. On the other hand, lower level releases may become imbedded in the drainage flow and move down the valley, or, emerge above the drainage flow upper boundary and impact (not intersect) on the valley wall or slope. Emissions from intense area sources (low-level) located in valleys and released into a very stable drainage flow or a deep, intense inversion layer will be severely restricted both horizontally and vertically.

Unless large obstacles are present, moderately rough natural topography will decrease the pollutant concentration by increasing mixing because of mechanical turbulence; therefore, the concentration levels measured will be less sensitive to the location of the site or placement of the instrument inlet. Wake cavities formed on the lee sides of the largest bluff obstacles may cause the downwash of a passing plume.

The effects on SO_2 plume behavior induced by vegetation are similar to those caused by irregular, rough terrain. However, an individual SO_2 plume passing over a clearing in a forest at a low level (viz., a low-level release from a nearby source) may be downwashed to the ground via a wake cavity formed on the windward side of the clearing.

5.2.2 Effects of Urbanization: General

The effect of urbanization on meteorological elements is described very well by Pooler (1963) and summarized by Peterson (1969). In their work, they discuss urban effects on the horizontal and vertical distributions of temperature, humidity, visibility, radiation, wind, and precipitation. The urban "heat island" phenomena has been well documented in studies by DeMarrais (1961), Mitchell (1961), Bornstein (1968), and Oke (1975). In these studies, characteristic vertical and horizontal variations, wind flows, and stability changes are discussed and compared to adjacent rural areas. Oke (1973) related city size and urban heat island intensity. Hutcheon, et al. (1967) show that even small cities can produce urban heat islands. From these studies, the effects of the various meteorological elements relevant to SO_2 behavior (and, therefore, monitoring site exposure criteria) are summarized here.

Nighttime temperatures in cities are higher than those observed over adjacent rural areas. Generally, the larger the city and more intense the nocturnal inversion, the larger the temperature differential between the urban core area and the outlying rural area (as great as 20°F). Heat island intensity has been shown to be related to the logarithm of population according to a study by Oke (1973) for a group of North American cities. Daytime temperature differentials are generally much less apparent than at night and occasionally are reversed.

Higher surface temperatures in urban areas reduce atmospheric stability. In fact, in large cities surface-based inversions are quite rare. Decreased stability, increased mixing depths, and increased mechanical turbulence, due to the rough urban topography, all tend to enhance the mixing and dispersion of pollutants.

Frictional drag and the urban heat island effect modify the urban wind direction. During the daytime, particularly under unstable conditions, wind directions over the cities and rural areas are reasonably homogeneous. However, at night the relatively warmer air of the city rises, causing low-level convergence and an inflow of air toward the urban center as observed by Pooler (1963). The inflow is strongest at night when the urban heat island is well developed. Of course, the magnitude of the effect is dependent on city size. In many cases, this inflow toward the urban center is observed whenever regional winds are weak. Often in extreme conditions, an outflow of urban air aloft is observed and results in a closed circulation.

5.2.2.1 Building-Induced Turbulence and Wakes

The material in this section is presented as support documentation for the criteria contained mainly in Tables 4-3 (see Page 39) and 4-5 (see Page 45).

The major area of concern here is the representativeness of urban monitoring sites in view of the complication in the wind and turbulence fields, particularly in the daytime, due to urban structures. Even the idealized situation of a single building is quite complex as shown in Figure 5-6. In cities, complex street canyon flows and cavity wakes on the lee side of buildings dominate the flow pattern. Since high SO_2 concentrations are often observed in urban areas (and is the rule in the north), a major effort was made to reflect in the urban site selection guidelines an accounting of such complex urban flow characteristics. In addressing the phenomena, some studies treating the problem by two basic techniques were reviewed--mathematical modeling (Hotchkiss and Harlow, 1973) and physical modeling (Halitsky, 1962). Neither technique provided comprehensive quantitative answers. However, each provided some insight into the problem. In general, features of complex urban flows are difficult to generalize via both mathematical and physical modeling because the dominant flow features near buildings cannot be represented as turbulence or as "potential flow" (i.e., a solution to the potential function equation).

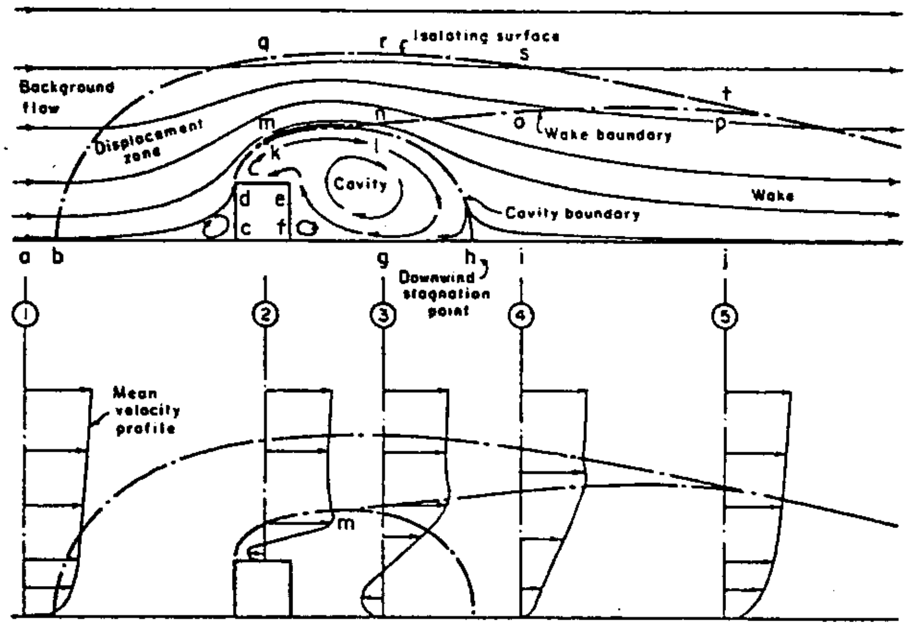


FIGURE 5-6. General arrangement of flow zones near a sharp-edged building (taken from Slade, 1968).

Cavity flows, as shown in Figure 5-7, and wake flows, as shown in Figure 5-8, contain features as large or larger than the obstacles creating them and yet are in no way random. They may, however, be embedded in random turbulence, and are, in general, dependent on very fine scale features of the flow such as the precise angle of incidence and the smoothness and precise shapes of the surface contours. Thus, numerical models which only introduce turbulence of a fixed intensity in the incident flow cannot reproduce the effect of the incident flow containing a regular train of eddies as large as the building.

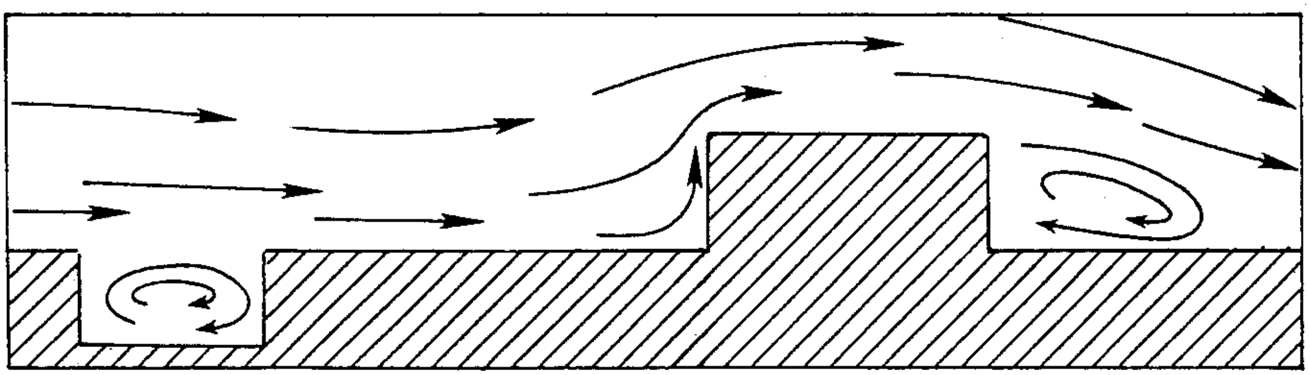


FIGURE 5-7. Cavity flows.

If models contain upstream structures to generate such eddies, they still cannot represent the formation or release rate of such eddies which depend on microscale surface details of the building.

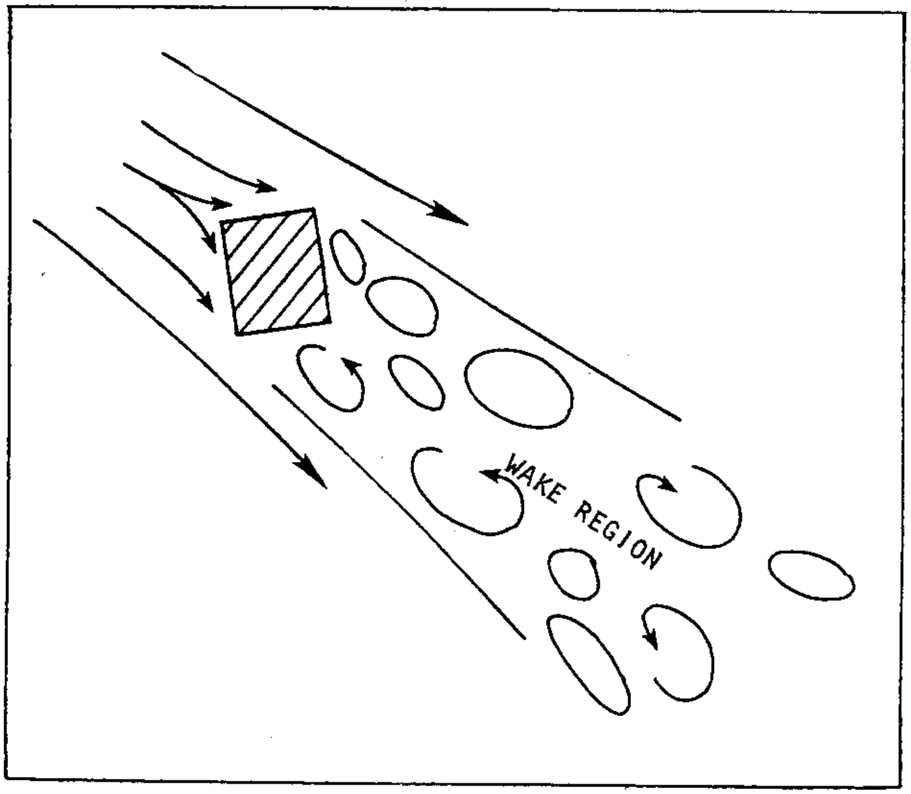


FIGURE 5-8. Wake region in flow past bluff obstacle (viewed from above).

A virtue shared by both numerical and physical modeling is that gross, qualitative features are quickly, cheaply, and/or distinctly shown, and the existence of large, coherent disturbances and their general nature can often be determined by such modeling programs. However, their location, size, typical residence time when trapped, or the pollutant concentrations resulting from plume interaction cannot usually be determined. For example, the wind tunnel studies described by Halitsky (1962), show that in some cases highest pollution flux is against the mean wind; whereas on superficially comparable building parts, no such reverse flow is evidenced. On other building roofs, pollutant transport is transverse to the mean wind. All of the observations might lead to conclusions that might be invalidated by slight changes in incident wind direction, or variability. The experiment does legitimately warn the selector of monitoring sites that one cannot easily or casually choose a site and be sure that it will be upwind (statistically) of a nearby source in a complex structural environment. However, in a later study, Drivas and Shair (1974) showed that a reverse circulation in the wake downwind of a building generally exists and that tracer experiments indicated that the extent of the recirculation back onto the roof was, in general, systematically confined to less than one-half the width of the building from the downwind edge.

5.2.3 Relevance of Above Considerations on Siting Criteria

The urban modifications to the regional meteorology that have a major impact on SO_2 concentrations and patterns are the air inflow characteristics under stable conditions when regional winds are weak, particularly at night, and the effects of wake cavities on the lee sides of buildings under stronger regional wind conditions.

When a heat island circulation exists, individual pollutant plumes may tend to converge toward the center of the city where they will rise, then return aloft to the periphery of the urban area and return again, completing the circulation (convergence at low levels, divergence aloft (see Figure 5-9). With a large number of SO_2 plumes tending to converge toward one central point and the return from aloft of already polluted air, a pollutant maximum may be located near the urban center. From heat island circulation dynamics, Chandler (1968) deduced that urban-rural pollution gradients would be very sharp with the strongest gradients on the lee side of the city. Ball (1969) observed that pollutant peaks roughly coincided with the thermal maximum of New York City's heat island and that the thermal pattern shifted and elongated in response to the regional wind flow.

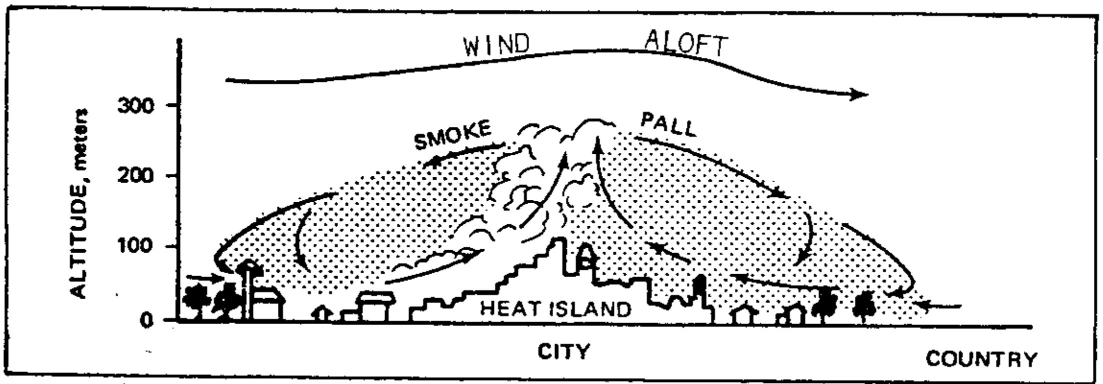


FIGURE 5-9. Urban circulation and dispersion before sunrise.

Under stronger wind speed conditions, particularly during the day, heat island circulations break down and lose their identity. Complex building wake patterns then distort the wind flow resulting in a very turbulent urban atmosphere, and become a major factor in influencing SO_2 concentrations and distributions. Figures 5-10 and 5-11 show mathematical representations of the effects of building wakes and cavity flows on pollutant distribution. In a large urban area, these complex flows would typically produce an averaging effect in both the horizontal and vertical. This statement is suppprted by Pelletier (1963) who measured SO_2 distributions in Paris; at specific locations he found no appreciable difference in 24-hour mean SO_2 concentrations measured at 13 m and 53 m above the ground. The same conclusions were reached by Clifton, et al. (1959) in a Sheffield, England study, particularly for locations not too near the upwind edge of the city (to allow sufficient time and distance for the wake/cavity-induced averaging effect to take place). Simon (1969) described a similar situation, in considerable detail, in his discussion of New York City's meteorology program. From the above considerations, what seems to emerge regarding the vertical distribution of SO_2 in urban areas is illustrated in Figure 5-12 and described as follows:

- A parcel of air entering the city is characterized by very low concentrations uniformly distributed in the vertical. At it passes through the suburbs, it picks up contributions from relatively small sources at low-to-moderate heights. As it passed through the central business district (CBD), very large amounts of SO_2 are picked up; but because of plume reflection and the mixing/averaging effect produced by building wakes, the SO_2 distribution is substantially uniform up to at least the mean building height. However, it is likely that a maximum concentration level may be observed above the mean building height near the mean effective height of the stronger sources which are emitted at higher levels. This statement is substantiated by Simon (1969, Fig.6). As the air leaves the city, the upper profile "fills in" due to the upward dispersion from lower levels. This effect plus horizontal dispersion continues until a vertically uniform, general low-to-moderate concentration level results just downwind of the city.

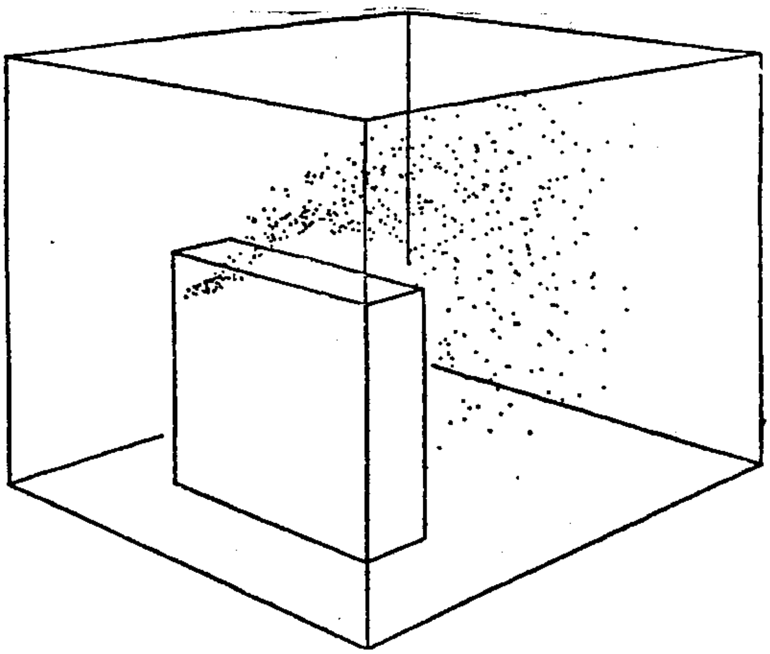


FIGURE 5-10.

The dispersal of a narrow plume passing over a single building. Recirculation in wake region is clearly evident. (Taken from Hotchkiss and Harlow, 1973.)

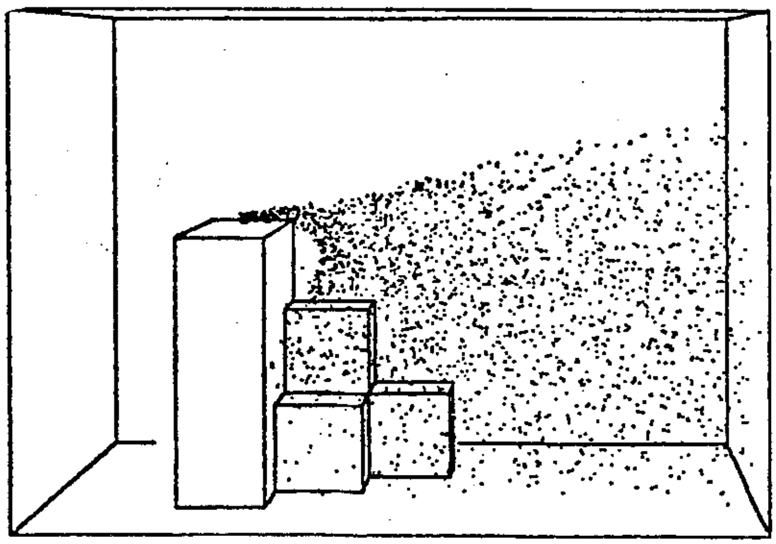


Figure 5-11.

The dispersal of pollutant from a flush vent on the top of a complex building structure. (Taken from Hotchkiss and Harlow, 1973.)

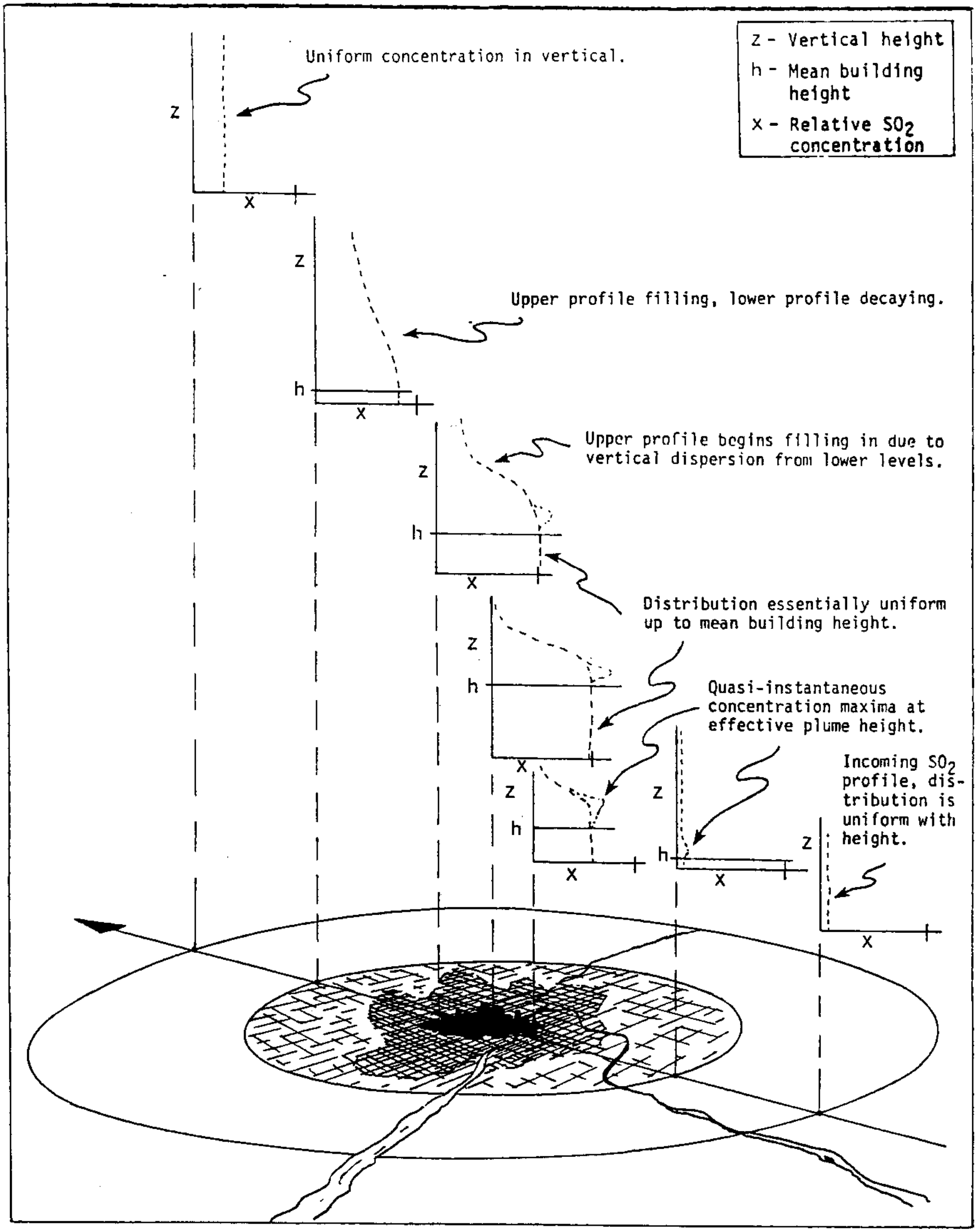


FIGURE 5-12. Schematic illustration of vertical distribution of SO_2 within a vertical column of air passing through an urban area.

From the above discussions, the following conclusions can be drawn:

- Mixing produced by mechanical turbulence and wake effects of larger obstacles over moderately rough, natural terrain averages the pollutant over space which lessens the concern of exact site location and inlet placement in rural areas.

- Micro-scale urban features substantially increase mixing and promote uniformity of pollutant levels from mid and far distant sources. This mixing between source and monitoring site, reduces the monitoring site selection problem to the consideration of only near sources (less than the interference distance).

- A single building wake can mix, over its volume, pollutant from a source that enters it. Thus, standard analyses compute a "virtual point source" upwind of a building if the building wake is thought to catch its own plume.

- The uniform mixing principle is not absolute and cavity flows often build, get swept away, and reform, leading to large "puff" type releases.

- Except for near the windward edge of a city, a vertically uniform SO_2 distribution up to at least the mean building height over the area of interest in the city can be assumed. The choosing of 0.8 $\bar{H}$ (or lower) for inlet location above the ground (see Table 4-3, Page 39; and Table 4-5, Page 45) is somewhat arbitrary, but was meant to insure that the instrument (or inlet) would be placed at a point in the vertical where the measured levels would approximate those existing near the breathing zone--5-6 ft above the ground.

- If pollutant release is known to be well within a cavity (e.g., emissions from a vehicle in a deep, street canyon) averaging will not be complete and concentration fluctuations and gradients are apt to be found within the flow. Minimum velocities and maximum concentrations should be found near the ground on the leeward side of the obstacle. This is the justification for avoiding trailer locations just downwind of buildings with large stacks (see Table 4-5). This situation is precluded, however, if the interference distance criteria are satisfied.

- Pollutants from sources located downwind of a building may be emitted into the wake cavity behind the building. The reverse flow of the wake may advect pollutants up to the roof of the building to at least one-half of the width of the building from the downwind edge. This observation is the rationale for recommending that inlet placement locations be on the windward side of the building (see Table 4-5). It also justifies the recommendation of not having SO_2 sources on the roof of the building chosen for the monitoring site or inlet location.

- Emergency episode stations should be located in the very heart of the maximum SO_2 emission density zone of an urban area; during air stagnations wind speeds are low and directions are variable so the maximum concentration should occur where the emission density is a maximum. However, even in this case, caution should be exercised in locating monitors. SO_2 emissions from high stacks (which are often the largest sources) may not reach the ground (if at all) until several miles away during a low wind-speed/stable situation. Appropriate site locations can best be found by using gridded emission inventory data with most of the weight being given to the area source fraction of the inventory.

- The heat island mechanism may produce maximum concentrations near the wind inflow convergence point which may be located near the center of maximum SO_2 emission zone of the city. This justifies considering the emergency episode station as an alternative site for measuring the 3-hour peak concentration.

5.3 MISCELLANEOUS CONSIDERATIONS

In this section, additional justification and rationale regarding certain siting criteria, modeling approaches and miscellaneous considerations along with support documentation is presented.

5.3.1 Temperature

The temperature at a point has little direct effect on the concentration of SO_2. Only temperature gradients, mainly in the vertical, have a major influence. However, temperature may influence the rate of emission of SO_2; for example, the amount of fuel burned for space heating is directly proportional to heating degree days, a number which is equal to the average temperature for the day minus 65°F. Turner (1968) and Roberts, et al. (1970) related SO_2 emission rate response to changes in temperature on an hourly (diurnal variation) as well as a daily mean basis. Power plant load (and SO_2 emissions) may vary seasonally and diurnally. In the northern part of the United States, power plant emission maxima occur in both summer and winter in response to power demand to run air conditioners (related to cooling degree days), and in response to demand to run electric and oil heating systems (related to heating degree days) (Federal Power Commission, 1971).

5.3.2 Chemical-Physical Interactions

SO_2, being soluble in water, interacts both chemically and physically with atmospheric moisture. SO_2 is also photochemically and catalytically reactive with other atmospheric constituents. The reaction kinetics of such interactions are very complex, all aspects of which are not yet fully understood. Some of the end products of atmospheric interactions involving SO_2 are sulfur trioxide, sulfuric acid, and sulfates. SO_2 also interacts with ground, vegetative, and water surfaces. Since it is beyond the scope of this report to present a detailed discussion of this topic, only a brief summary of the more pertinent aspects is presented.

5.3.2.1 Reactions of SO_2 With Atmospheric Liquid Water

Precipitation scavenging consists of three basic components as described by Slade (1968):

1) transport of the SO_2 to the scavenging site,

2) in-cloud scavenging by precipitation and cloud elements (rainout), and

3) below-cloud scavenging by falling raindrops (washout).

The rate of scavenging of SO_2 is based on the molecular diffusion of SO_2 to the droplets in accordance with the vapor pressures and solubility of SO_2. Laboratory tests by Bracewell and Gall (1967) indicated that the occurrence of H_2SO_4 in urban fogs could be accounted for by the catalytic oxidation of SO_2 dissolved in fog droplets in the presence of certain metallic ions.

5.3.2.2 Catalytic and Photochemical Oxidation Reactions

SO_2 may be catalytically oxidized to SO_3 in the presence of oxides of nitrogen. The SO_3 then readily converts basic oxides to sulfates (NAPCA,1970). Liberti and Devitofranesco (1967) reported that SO_2 may be catalytically oxidized to sulfate after being adsorbed by suspended particles. In a report to the U.S. Senate, the National Academy of Sciences (NAS, 1975) reported that SO_2 oxidation rates (to sulfates) varies from 0.17 percent/hour to 50 percent/hour, depending on the relative humidity and the presence and relative concentrations of other pollutants. The rate is typically more rapid in urban air. Urone, et al. (1968) reported that SO_2 can be photo-oxidized to H_2SO_4 aerosol in the presence of water vapor and at a faster rate when hydrocarbons and nitrogen dioxide are present. In the same NAS report cited above, it was estimated that in the northeastern United States, roughly one-third of SO_2 emissions are returned to the earth as sulfates.

5.3.2.3 Reactions With Ground and Water Surfaces

In a study by Spedding (1972), the ocean was found to be a major sink for SO_2. He concluded that SO_2 deposition velocities (V_g = deposition/surface area/time of exposure/atmospheric concentration) were proportional to the flow rate of the SO_2-air mixture. Under calm conditions, he estimated a value of V_g of 0.28 cm/sec. Owers and Powell (1974) estimated an SO_2 deposition velocity of 0.8 cm/sec over land and water surfaces. Similar values were found by Shepard (1974) for grass in summer but were much less in the autumn (0.3

cm/sec). Over water he found that V_g was proportional to windspeed. Garland, et al. (1974) reported a deposition velocity of 0.55 cm/sec onto short grass. Individual values varied widely and were independent of the weather. He also estimated that 25 percent of the SO_2 emitted within Great Britain was deposited by dry deposition.

5.3.2.4 Residence Times and Half-Life

Residence times and half-lives of SO_2 are extremely variable because of the very complex interactions of SO_2 with other reactive pollutants, atmospheric liquid and gaseous water, surface water, land and vegetative surfaces, sunshine, and weather. Eliassen and Saltbones (1975) reported a residence time for SO_2 of about one-half day, or a decay rate of about .002 percent/sec. In their work, they considered dry deposition and oxidation to sulfates.

In general, the various oxidation/deposition rates for SO_2 as summarized above correspond to half-lives ranging from about one hour to several days. The shorter half-lives are probably characteristic of urban SO_2 where sufficient quantities of reacting pollutants exist to hasten the transformation process.

Figure 5-13 is a schematic showing SO_2 transport, diffusion, and various removal processes.

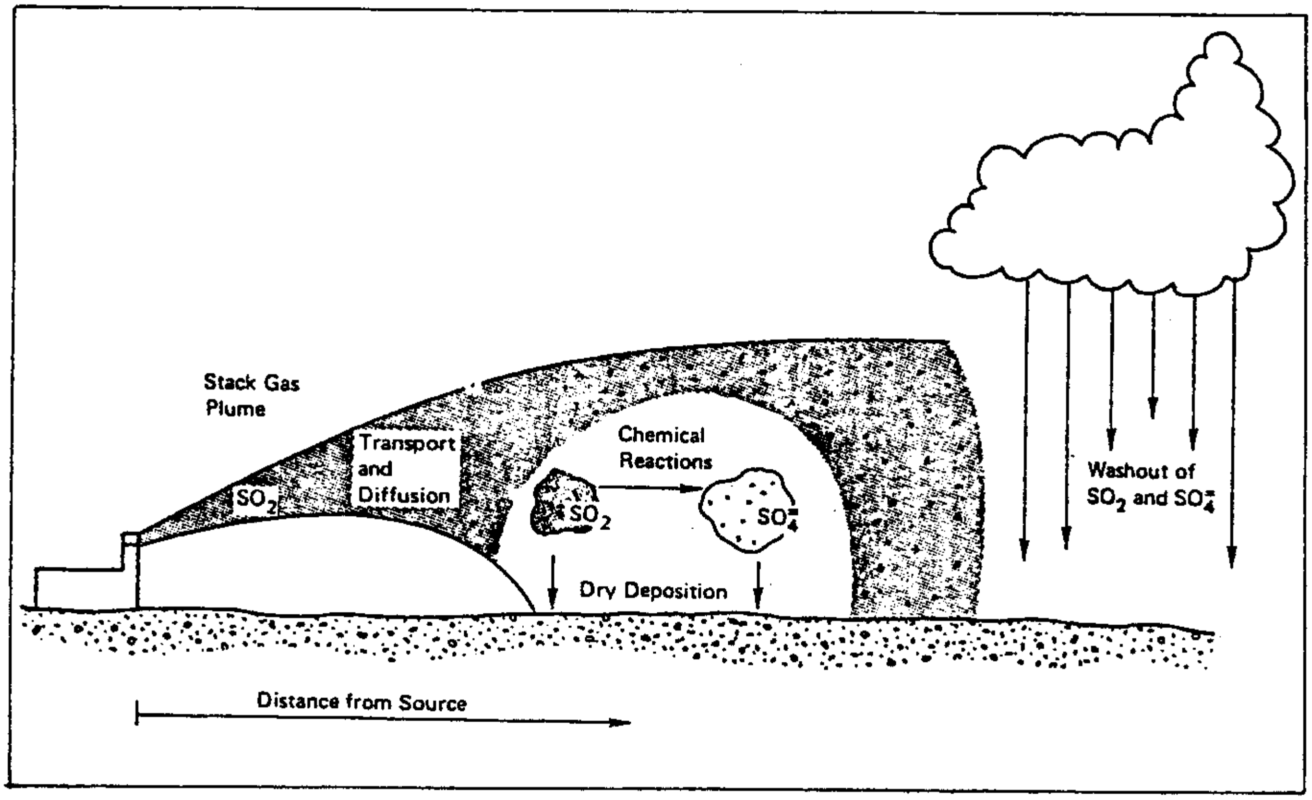


FIGURE 5-13. Processes involved in the relationship of sulfur oxide emissions to air quality (taken from NAS, 1975).

5.3.2.5 SO_2 Reactivity and Monitoring Device Inlet Tubes

Because of the adsorption-desorption characteristics of SO_2, care must be taken in choosing the kinds of inlet tubes for SO_2 monitoring devices. Stainless steel, glass, and teflon have been shown (Wohlers, et al., 1967) to be nonreactive for either high flow (28.3 l/min) or low flow (1.4 l/min) sampling through 30.5 m lengths (1.27 cm i.d.) of tubing made from such material.

5.3.3 Relevance of Above Considerations to Siting Criteria

Ambient temperature levels dictate the amount of fuel to be consumed for space heat. Since the coldest temperatures occur in winter, the prevailing wind direction for the three core winter months (December, January, and February) was considered as the "upwind" direction for determining the sources most frequently upwind of prospective monitoring sites.

The very complex problem regarding the chemical/physical interactions of SO_2 was addressed by assuming that SO_2 decays exponentially with a half-life of three hours, generally, but one hour for cities of over 10^6 population. The population figure is somewhat arbitrary, but the objective was to address the fact that the chemical conversion of SO_2 in the largest urban areas proceeds at a faster rate than in rural areas. Using an appropriate half-life value in all modeling exercises is important, particularly for assessing point sources in urban settings and in the process of determining the sizes of projected growth or population areas to be represented by either neighborhood or middle-scale stations (see Section 4.3.2). In the former, the contribution of SO_2 at the monitoring site due to the source is a function of transit time (and half-life) as well as distance; in the latter, the concentration gradient is a function of half-life. In the same section (4.3.2), the 0.5 $\mu g/m^3$ - km gradient value is arbitrary; it was considered a realistic threshold value separating steep and flat concentration gradients and was chosen via inspection of SO_2 concentration maps. Also, in the same section, the extreme concentration value span of $\pm$ 25 percent of the mean concentration over an area, for determining whether one monitoring site will represent concentrations over the area, is also arbitrary. However, this value, considered as reasonable for most purposes as given, could be adjusted to satisfy any purpose at the discretion of the site selector.

The remaining siting and inlet placement criteria of Table 4-3 (see Page 39) and Table 4-5 (see Page 45) not specifically addressed above are consistent with those found in existing guidelines (e.g., EPA, 1971, 1974b). They are recommended mainly to prevent contamination of the instrument from dust sources on the roof of the site building or to insure a proper exposure to the open ambient air stream.

Quiz 2

Take this quiz to determine whether you have mastered the objectives of reading assignments 3 and 4 before you take the final exam.

Do *not* use your notes or books. You may use a protractor and ruler. Take no more than thirty minutes to complete the quiz. Check your answers against the answer key that follows. Review the pages indicated for any questions you missed.

1. In a sea-breeze situation, vertical mixing depth ________ as the terrain slopes ________ from flat terrain.

   a. increases, upward

   b. increases, downward

   c. decreases, upward

   d. decreases, downward

2. As an air parcel passes between two obstructions, the parcel's speed ________.

   a. decreases

   b. increases

   c. remains the same

3. The major effect of moderately rough terrain on a plume is to ________ its rate of dispersal.

   a. increase

   b. decrease

   c. there is no effect on dispersal rate

4. As an air parcel passes across a valley, the parcel's speed ________.

   a. increases

   b. decreases

   c. remains the same

5. True or False? The urban heat-island effect causes air to flow around urban centers at night.

6. True or False? Stack downwash conditions may occur if the ratio between the stack gas velocity and the wind velocity is less than about 1.5.

7. True or False? An undue influence SO_2 concentration level of 0.1 mg/m^3 was used in determining the regional scale interference distances.

8. True or False? When monitoring SO_2 impacts from an isolated point source that is located in extremely rough terrain, monitoring stations should be established at ridgetop locations in the general downwind directions from the point source.

9. True or False? For cities with populations of one million or less, the SO_2 siting criteria are based on an assumed SO_2 half-life of three hours.

10. True or False? An undue influence SO_2 concentration level of 10 mg/m^3 was used in determining point source, minor source, and source interference distances.

11. True or False? Under stable atmospheric conditions, air parcels tend to move over obstacles.

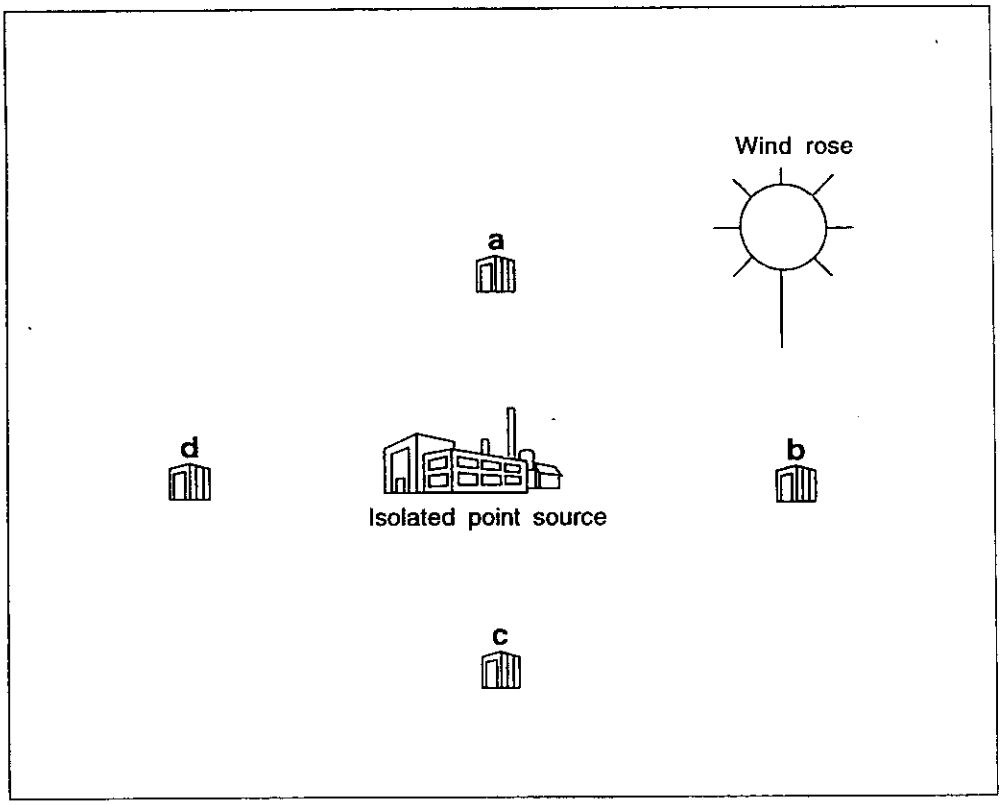
12. True or False? An SO_2 source has more influence on SO_2 concentrations measured at monitoring sites within its 10-degree plume sector than at sites outside its 10-degree plume sector.

13. True or False? At night, upslope air flows are caused by cooling of the air adjacent to the ground along a valley floor and slope.

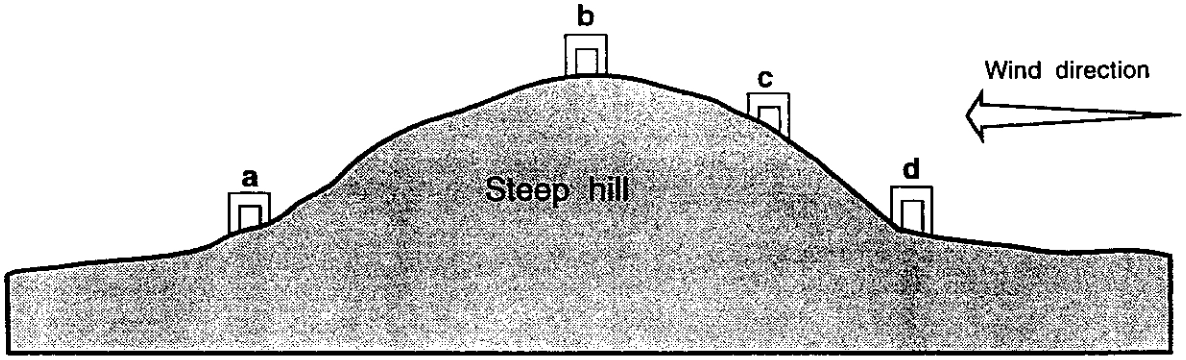
14. True or False? An air cavity tends to increase pollutant concentrations.

15. True or False? Mountain passes increase wind speeds.

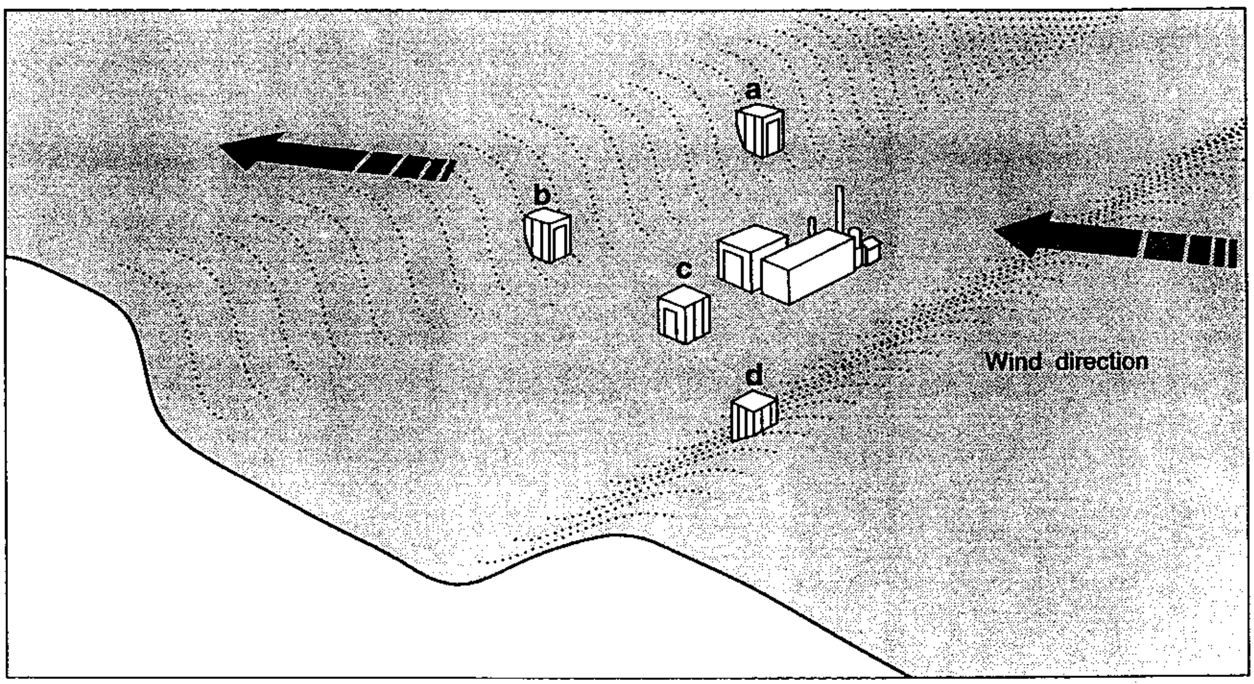
16. Which of the four general siting areas, labeled a through d, is the best siting area for a monitoring station for determining peak SO_2 concentrations resulting from the isolated point source?



17. Which of the locations, labeled a through d, would be the most likely site of an air cavity wake?

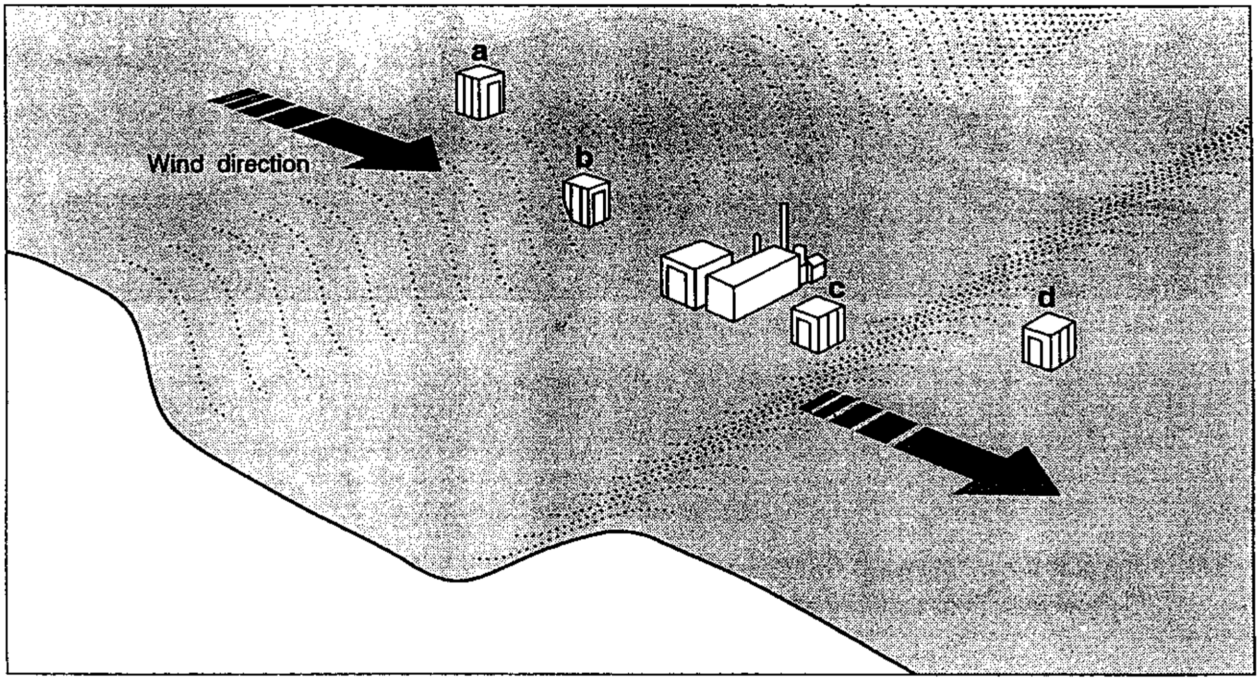


18. **Which of the four general siting areas, labeled a through d, is the best siting area for determining peak SO_2 concentrations resulting from the point source?**



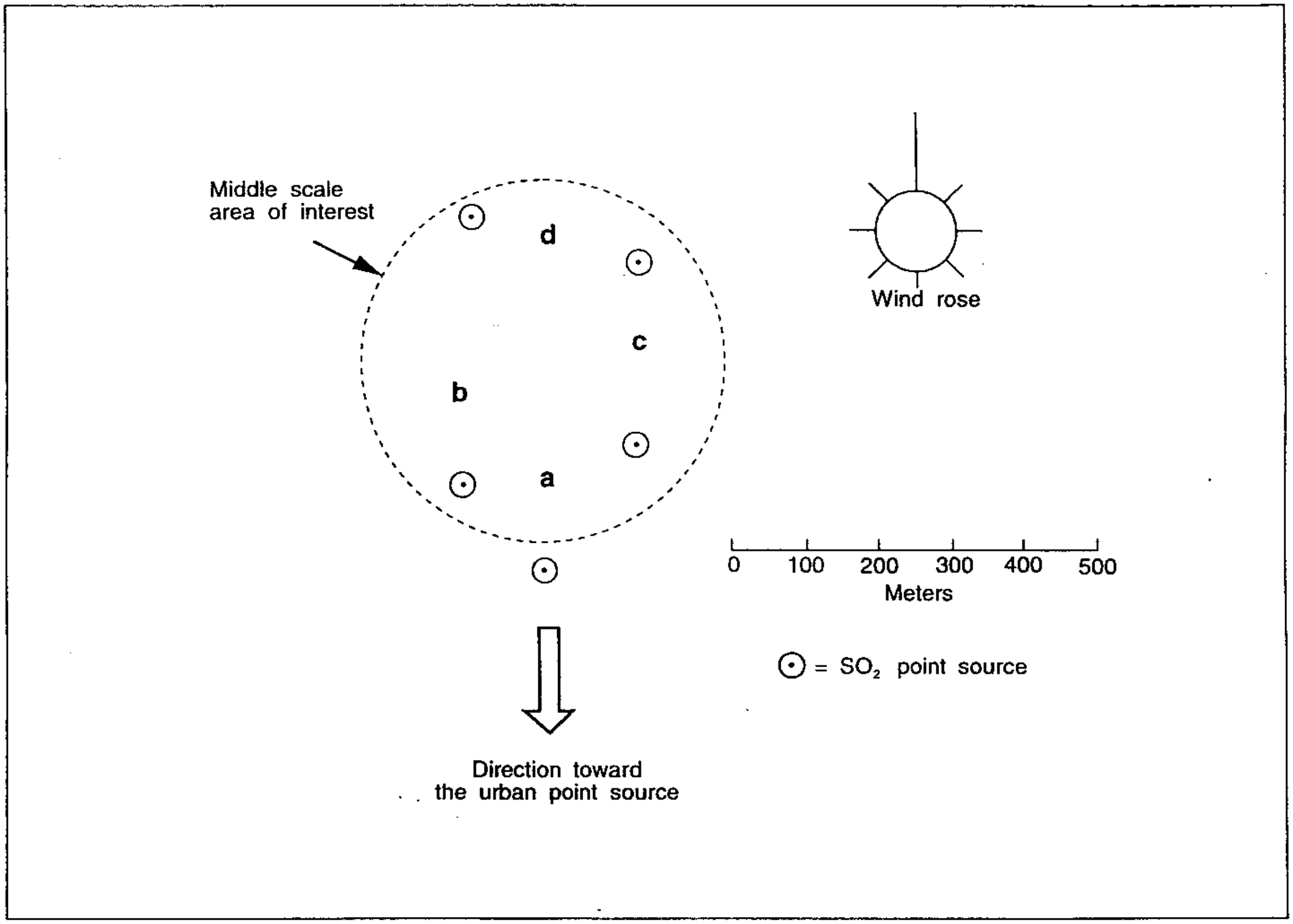
Stable atmospheric conditions, light to moderate wind

19. Which of the four general siting areas, labeled a through d, is the best siting area for determining peak SO_2 concentrations resulting from the point source?



Unstable atmospheric conditions

20. Which of the four general siting areas, labeled a through d, is the best siting area for a proximate middle scale monitoring station for determining the maximum annual SO_2 impact from the urban point source?



Quiz 2 Answer Key

		Page*
1.	a	66
2.	b	88
3.	a	77
4.	b	88
5.	False	92
6.	True	61
7.	False	84
8.	True	82
9.	True	102
10.	True	85
11.	False	91
12.	True	87
13.	False	90
14.	False	89
15.	True	90
16.	a	62
17.	a	89
18.	b	72-73
19.	d	72-73
20.	d	54-56

* Refer to EPA-450/3-77-013 *Optimum Site Exposure Criteria for SO_2 Monitoring.*